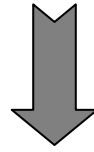


# APS Multi-Divisional Neutrino Study

Boris Kayser  
HEPAP Meeting  
September 23, 2004

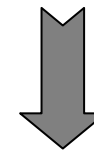
The last six years



Compelling evidence that  
neutrinos have mass and mix



Open questions about  
the neutrino world



Need for a coherent strategy  
for answering them

This need has led to a year-long study of the future of neutrino physics, sponsored by the **APS Divisions** of –

**Nuclear Physics**

**Particles and Fields**

**Astrophysics**

**Physics of Beams**

# The Primary Purpose of the Study

To move towards a coherent strategy for answering the open neutrino questions — a clear, unified plan that funding sources can easily consider and promote.

The findings should help guide the creation of the future neutrino program.

To quote the Charge —

“The Study will lay scientific groundwork for the choices that must be made during the next few years.”

A grassroots study like this, co-sponsored by several APS Divisions, is unprecedented.

It aims at consensus, which is not a trivial goal.

## — Secondary Purpose —

To explain to our colleagues in other areas of physics, to our funding sources, and to the general public why neutrino physics is now so exciting.

The study website: [www.interactions.org/neutrino study](http://www.interactions.org/neutrino study)

# The Structure of the Study

## Chairmen

Stuart Freedman, Boris Kayser

## Organizing Committee

Janet Conrad, Guido Drexlin,  
Belen Gavela, Takaaki Kajita,  
Paul Langacker, Keith Olive,  
Bob Palmer, Georg Raffelt,  
Hamish Robertson, Stan Wojcicki  
Lincoln Wolfenstein

# Working Groups — The Central Element

Each working group is defined by an experimental approach.

The groups and their leaders —

## Solar and Atmospheric Neutrino Experiments

John Bahcall <jnb@ias.edu>, Josh Klein <jrk@physics.utexas.edu>

## Reactor Neutrino Experiments

Gabriela Barenboim <gabriela@fnal.gov>, Ed Blucher <blucher@hep.uchicago.edu>

## Superbeam Experiments and Development

Bill Marciano <marciano@bnl.gov>, Doug Michael <michael@hep.caltech.edu>

## Neutrino Factory and Beta Beam Experiments and Development

Stephen Geer <sgeer@fnal.gov>, Michael Zisman <mszisman@lbl.gov>

## Neutrinoless Double Beta Decay and Direct Searches for Neutrino Mass

Steve Elliott <elliotts@lanl.gov>, Petr Vogel <pxv@caltech.edu>

## What Cosmology/Astrophysics and Neutrino Physics can Teach Each Other

Steve Barwick <barwick@HEP.ps.uci.edu>, John Beacom <beacom@fnal.gov>

## Theory Discussion Group

Rabi Mohapatra <rmohapat@physics.umd.edu>



The Organizing Committee plus the Working Group Leaders form the Coordinating Committee.

The Coordinating Committee guides the study.

The final study report is being written by the —

Writing Committee

Hamish Robertson

(Chair)

Janet Conrad, Andre de Gouvea,

Steve Elliott, Stuart Freedman,

Maury Goodman, Boris Kayser,

Josh Klein, Doug Michael

This submits its work to the Coordinating Committee.

# What Has Happened?

The working groups have done a great deal of work, mostly separately but sometimes in concert. They have summarized their findings in their working group reports.

A general meeting was held in Snowmass to permit wide-ranging discussion and the stating of opinions.

With the working group findings and the Snowmass discussion as input, the Writing Committee has been working on the cross-cutting heart of the study's final report.

# The Status of the Study

It ain't over 'til it's over.

The final report has been submitted to the Coordinating Committee for comment.

The thrust of most of our major conclusions is fairly clear.

I will try to convey the flavor of them to you.

A funding agency briefing is planned for late October.

# The Neutrino Scene

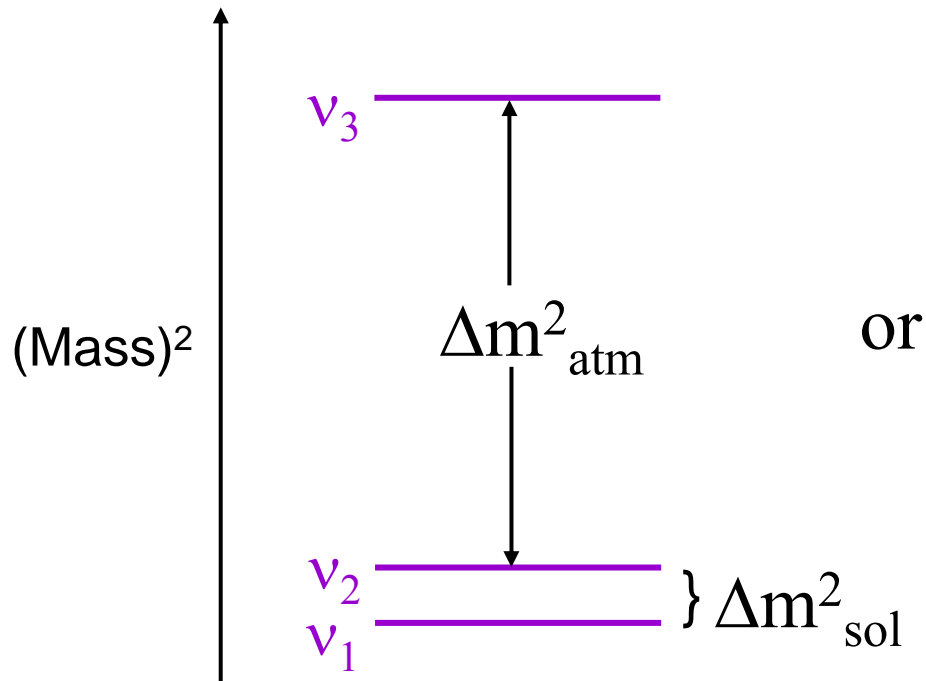
We do not know **how many** neutrino mass eigenstates there are.

If the **Liquid Scintillator Neutrino Detector (LSND)** experiment is confirmed, there are **more than 3**.

If **LSND** is not confirmed, nature may contain **only 3** neutrinos.

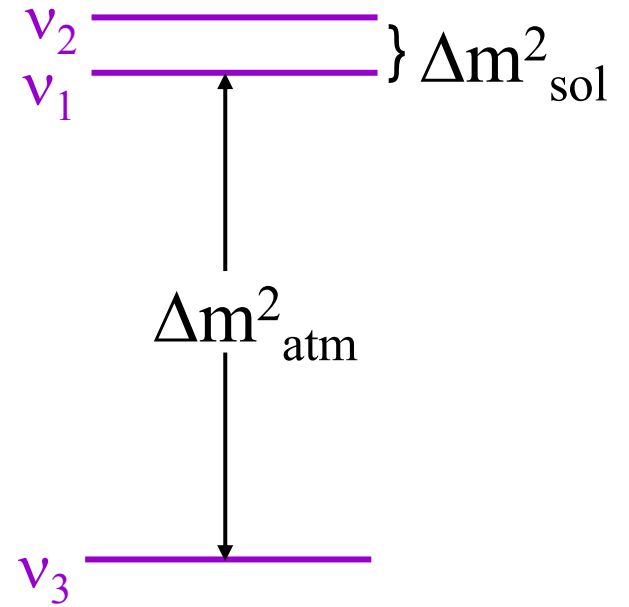
Then, from the existing data, the neutrino spectrum looks like —

Normal



or

Inverted

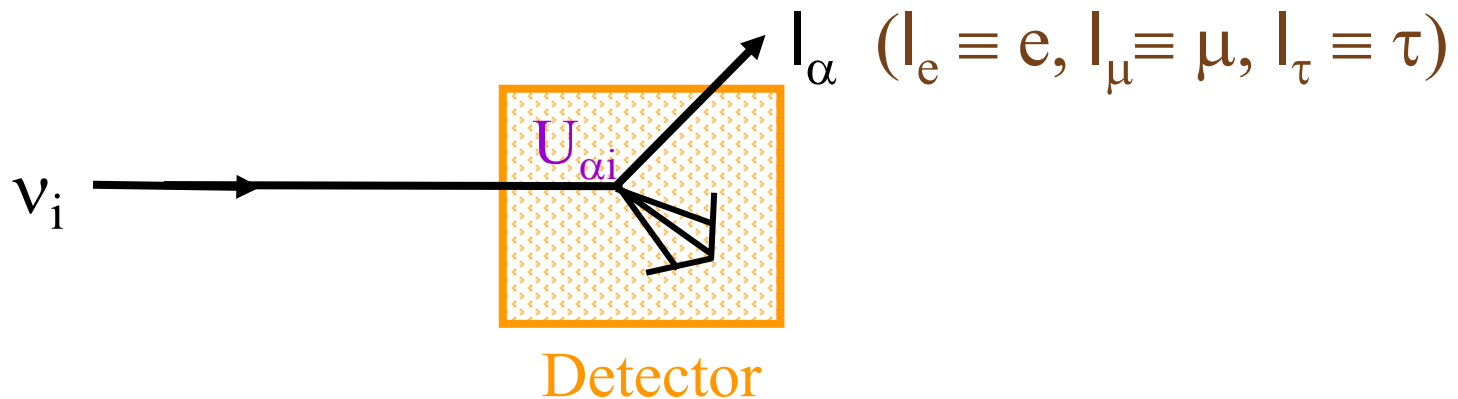


$$\Delta m^2_{\text{sol}} \simeq 8 \times 10^{-5} \text{ eV}^2, \quad \Delta m^2_{\text{atm}} \simeq 2.5 \times 10^{-3} \text{ eV}^2$$

Generically,  $SO(10)$  grand unified models predict  $\underline{\underline{\quad}}$ .

$\underline{\underline{\quad}}$  is un-quark-like, and would probably involve a lepton symmetry with no quark analogue.

# The Unitary Leptonic Mixing Matrix $U$

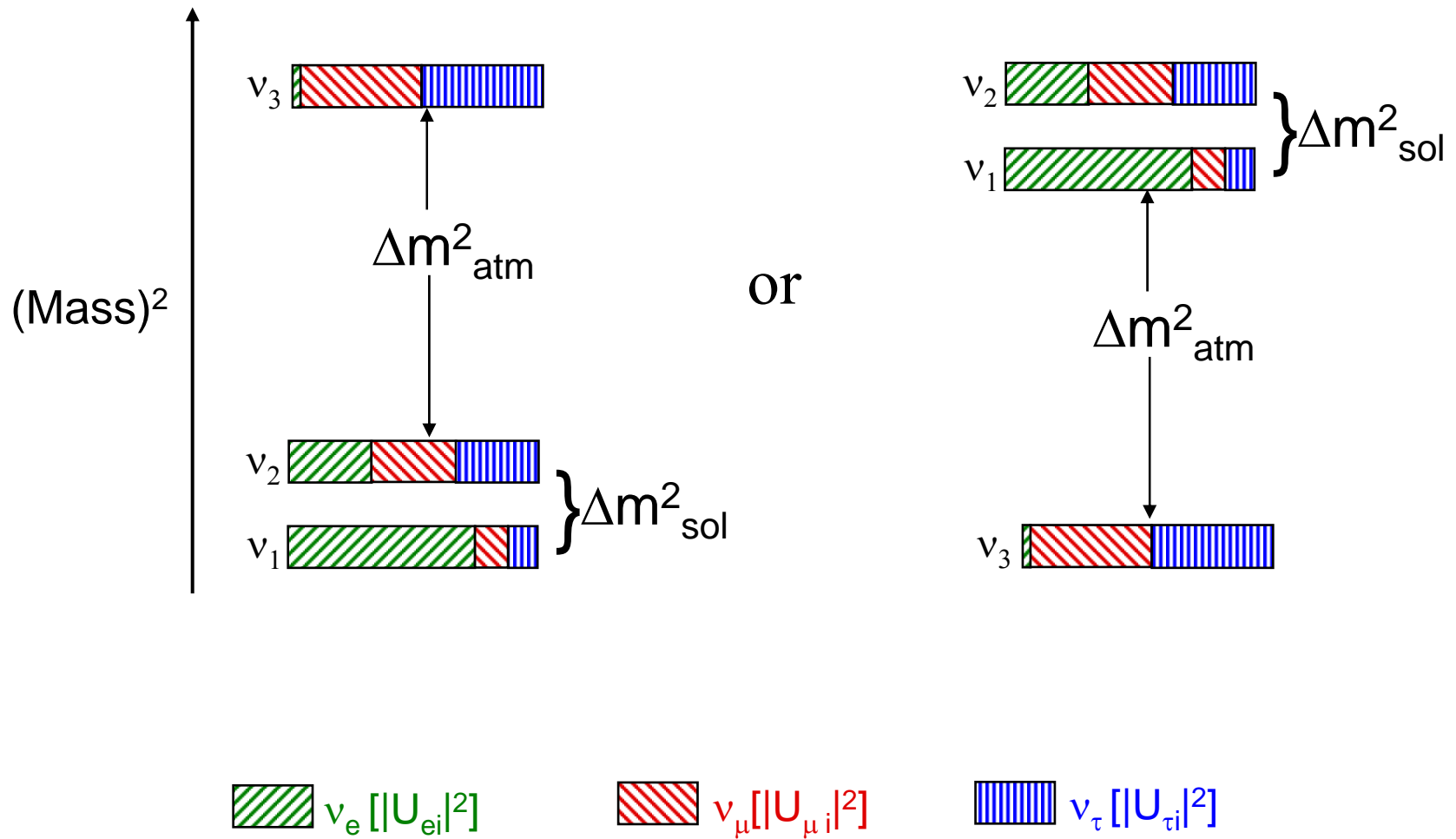


The component of  $v_i$  that creates  $l_\alpha$  is called  $v_\alpha$ .  
the neutrino of flavor  $\alpha$ .

The  $v_\alpha$  fraction of  $v_i$  is  $|U_{\alpha i}|^2$ .



The spectrum, showing its flavor content, is —



# The Mixing Matrix

$$U = \begin{array}{c} \text{Atmospheric} \\ \left[ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{array} \right] \end{array} \times \begin{array}{c} \text{Cross-Mixing} \\ \left[ \begin{array}{ccc} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{array} \right] \end{array} \times \begin{array}{c} \text{Solar} \\ \left[ \begin{array}{ccc} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{array} \right] \end{array}$$

$$\times \left[ \begin{array}{ccc} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{array} \right]$$

$$\begin{array}{l} c_{ij} \equiv \cos \theta_{ij} \\ s_{ij} \equiv \sin \theta_{ij} \end{array}$$

$$\theta_{12} \approx \theta_{\text{sol}} \approx 32^\circ, \quad \theta_{23} \approx \theta_{\text{atm}} \approx 35\text{-}55^\circ, \quad \theta_{13} \lesssim 15^\circ$$

Majorana ~~CP~~  
phases

$\delta$  would lead to  $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$ . ~~CP~~

But note the crucial role of  $s_{13} \equiv \sin \theta_{13}$ .

# The Open Questions

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# Neutrinos and the New Paradigm

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- What are the masses of the neutrinos?
- What is the pattern of mixing among the different types of neutrinos?
- Are neutrinos their own antiparticles?
- Do neutrinos violate the symmetry CP?

# Neutrinos and the Unexpected

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- Are there “sterile” neutrinos?
- Do neutrinos have unexpected or exotic properties?
- What can neutrinos tell us about the models of new physics beyond the Standard Model?

# Neutrinos and the Cosmos

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- What is the role of neutrinos in shaping the universe?
- Is CP violation by neutrinos the key to understanding the matter – antimatter asymmetry of the universe?
- What can neutrinos reveal about the deep interior of the earth and sun, and about supernovae and other ultra high energy astrophysical phenomena?

# Highlights of the Study

## Conclusions

**PRELIMINARY**

The conclusions are still under discussion.

But fairly broad consensus has emerged  
on a number of issues.

# The Context

Our recommendations for a strong future program are predicated on fully capitalizing on our investments in the current program:

- Accelerator  $\nu$  experiments within the U.S.
- American participation in experiments in Antarctica, Argentina, Canada, Germany, Italy, and Japan



The current/near-future program should include –

- Determination of the  $^7\text{Be}$  solar neutrino flux to 5%.
- Clear-cut confirmation or refutation of LSND.
- R&D on techniques for detecting astrophysical neutrinos above  $10^{15}$  eV.
- Measurements of neutrino cross sections needed for the interpretation of neutrino experiments.

# An Important Observation

The **future experiments** we feel are particularly important rely on suitable **underground facilities**. Having these facilities will be crucial.

# Proto – Recommendations for Future Experiments

# High Priority: A phased program of searches for neutrinoless double beta decay ( $0\nu\beta\beta$ )

Observation of  $0\nu\beta\beta$  would establish that –

- Lepton number  $L$  is not conserved
- Neutrinos are Majorana particles ( $\bar{\nu} = \nu$ )
- Nature (*but not the Standard Model*) contains Majorana neutrino masses

# Why Many Theorists Think L Is Not Conserved

The Standard Model (SM) is defined by the fields it contains, its symmetries (notably Electroweak Isospin Invariance), and its renormalizability.

Anything allowed by the symmetries occurs.

The SM contains no  $\nu_R$  field, only  $\nu_L$ , and no  $\nu$  mass.  
This SM conserves L.

But now we know the neutrino does have mass.

If we try to preserve conservation of L, we accommodate this mass by adding to the SM a Dirac, L - conserving, mass term:  $m_D \nu_L \bar{\nu}_R$ .

To add the Dirac mass term, we had to add  $\nu_R$  to the SM.

Unlike  $\nu_L$ ,  $\nu_R$  carries no Electroweak Isospin.

Thus, no SM symmetry prevents the occurrence of the Majorana mass term  $m_M \overline{\nu_R^c} \nu_R$ .

This mass term causes  $\nu \rightarrow \bar{\nu}$ . It does not conserve L. (Thus, the  $\nu_i$  will be Majorana particles.)

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$$\text{Lifetime } (0\nu\beta\beta) \propto 1/[m_{\beta\beta}]^2$$

A phased  $0\nu\beta\beta$  program addressing three possible  $m_{\beta\beta}$  ranges:

Range (meV)	Spectrum Covered	Required Mass	Status
100 – 500	Quasi - Degenerate	200 kg	Close
20 – 50	Inverted	1 ton	“Proposed”
2 – 5	“Any”	100 tons	Future Tech.

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In the first two stages, more than one experiment is desirable, worldwide, both to permit confirmation and to explore the underlying physics.

# High Priority: A comprehensive U.S. program to –

- Complete our understanding of neutrino mixing
- Determine whether the neutrino mass spectrum is normal or inverted
- Search for CP violation among the neutrinos



# Components of this Program

- A rapidly – deployed reactor experiment with sensitivity down to  $\sin^2 2\theta_{13} = 0.01$

The size of CP violation and the ability to tell whether the mass spectrum is normal or inverted both depend on  $\theta_{13}$ .

If  $\sin^2 2\theta_{13} < 0.01$ , a neutrino factory will be needed to study both of these issues.

A relatively modest-scale reactor experiment can cleanly determine whether  $\sin^2 2\theta_{13} > 0.01$ , and measure it if it is.

## Sensitivity:

<u>Experiment</u>	<u><math>\sin^2 2\theta_{13}</math></u>
Present CHOOZ bound	0.2
Double CHOOZ	0.03 (In $\sim$ 2013)
Future US experiment (Detectors at $\sim$ 200 m and $\sim$ 1.5 km)	0.01

- A timely accelerator experiment with the possibility of determining the character of the mass hierarchy

An accelerator  $\nu$  experiment can probe several neutrino properties.

Only the U.S. can have baselines long enough to probe whether the spectrum is normal or inverted.

# Why are long baselines needed?

At superbeam energies,

$$\sin^2 2\bar{\theta}'_M \cong \sin^2 2\theta_{13} \left[ 1 \pm \text{Sign}[m^2(\text{---}) - m^2(\text{==})] S \frac{E}{6 \text{ GeV}} \right].$$

At oscillation maximum,

$$\frac{P(\nu_\mu \rightarrow \nu_e)}{P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \begin{cases} > 1 ; & \text{---} \\ < 1 ; & \text{==} \end{cases}$$

The effect is  $\begin{cases} 30\% ; & E = 2 \text{ GeV (NOvA)} \\ 10\% ; & E = 0.7 \text{ GeV (T2K)} \end{cases}$

Larger E is better.

But want  $L/E$  to correspond roughly to the peak of the oscillation.

Therefore, larger E should be matched by larger L.

Using larger L to determine whether the spectrum is normal or inverted could be a unique contribution of the U.S. program.

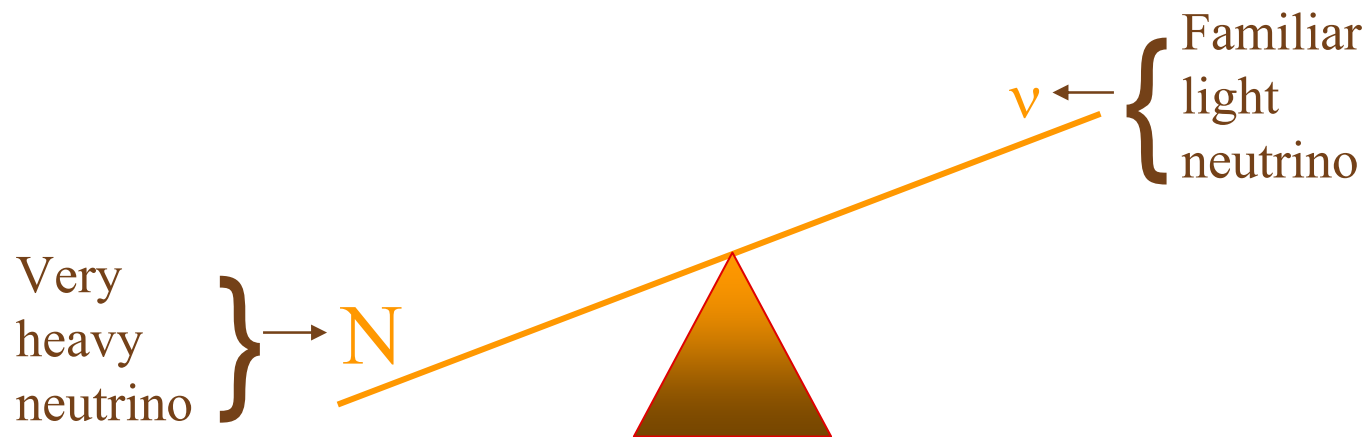
- A multi-megawatt-class proton driver and neutrino superbeam with an appropriate large detector capable of observing CP violation

These facilities are needed if we are to be able to determine whether the spectrum is normal or inverted, and to observe CP violation, for any  $\sin^2 2\theta_{13} > (0.01 - 0.02)$ .

# Why would $\cancel{CP}$ in $\nu$ oscillation be interesting?

The most popular theory of why neutrinos are so light is the —

## See-Saw Mechanism



The heavy neutrinos  $N$  would have been made in the hot Big Bang.

If neutrino oscillation violates CP, then quite likely so does  $N$  decay.

Then, in the early universe, we would have had different rates for the CP-mirror-image decays –

$$N \rightarrow \ell^- + \dots \quad \text{and} \quad N \rightarrow \ell^+ + \dots$$

This would have led to unequal numbers of leptons and antileptons (Leptogenesis).

Perhaps this was the original source of the present preponderance of **Matter** over **Antimatter** in the universe.



# Important: An Experiment That Can Measure the Energy Spectrum of the pp Solar Neutrinos

The pp neutrinos are almost *all* the neutrinos.

- Confirm the Mikheyev-Smirnov-Wolfenstein explanation of solar neutrino behavior
- Test whether the pp fusion chain is the only source of solar energy

# Looking Ahead, and Keeping Our Eyes Open

- A neutrino factory (or beta beam) is the ultimate tool in neutrino physics. It may be the *only* way to study CP violation and other issues. Substantial neutrino factory R&D is needed if this facility is to be possible in the long term.
- Worldwide, at least two detectors sensitive to a galactic supernova should be operational at any given moment.

# Conclusion

We have a very rich opportunity to do  
exciting physics.

Let's use it wisely.